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ALGEBRAIZATION OF A PROBLEM IN REGULATION THEORY BY MEANS OF AUTOMATIC CALCULATORS

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The present article is part of a lecture read by the author in Prof L. A. Lyusternik's seminar on approximate calculations at Moscow State University. It is devoted to a problem presented at this seminar by I. Ya. Akushskiy and formulated in Akushskiy's article, "An 'Extremal' Problem on the Use of Selectors in Computing-Analytical Machines" (Uspekhi Matematicheskiy Nauk, Vol II, No 4, 1947). This problem concerns the theory of regulation by automatic calculators by means of selectors (vide I. Ya. Akushskiy's article, "Computing Analytical Machines and Certain of Their Applications to Mathematical Problems," Chapter II, Section 6, in Trudy Matematicheskogo Instituta imeni V. A. Steklova, Vol XX, 1947). These selectors are special relay systems that distribute the input impulses entering the machine among the operating parts of the machine (the selectors can, for example, distribute the numbers punched on punch cards, called "perfokarts," among the calculators; the selectors are regulated by special perforations on the punch cards). This problem is reduced in the well-known sense to the problem formulated below from the theory of substitution groups. Generally, the problems of automatic regulation, or control, often bear a combinatorial character and can be formulated algebraically.

Let a machine possess k counters $s_1, s_2, \ldots s_k$. Each of the punch cards is divided into k sections $D_1, D_2, \ldots D_k$, in which numbers are punched. To realize the substitution

$$S = \begin{pmatrix} 1, & 2, & \ldots, & i, & \ldots, & k \\ r_1, & r_2, & \ldots, & r_i, & \ldots, & r_k \end{pmatrix}$$

means to direct a number standing in each section D_i to the corresponding counter s_{ri} $(i = 1, 2, \ldots k)$. In all, we have factorial-k (k!) such substitutions of the symmetric group $S^{(k)}$, which are designated $S_1, S_2, \ldots S_{k!}$ hereafter. Furthermore, we have a certain block of punch cards, which is divided into partial blocks $M_1, M_2, \ldots. M_{k!}$. It is required that each punch card from the partial block M_j $(j = 1, 2, \ldots. k!)$ realize a corresponding substitution S_j. As shown in Akushskiy's above-mentioned article on an extremal problem, this can

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be attained with the aid of a certain number p of selectors (by regulated systems of notches on the cards; for all cards entering one and the same block M_j, the system of notches must be the same).

In the same article, I. Ya. Akuskskiy proposes the problems: (1) the minimum number p of selectors able to realize all factorial-k, k!, permutations of the symmetric group $S^{(k)}$, and also (2) the commutation combining these selectors and the system of cuts, called "adsec's," assuring the realization of each such substitution.

Proceeding to the algebraization of the problem, we note first that a combination, or set, of two (class one) selectors brings about a transposition of the impulses. Actually, we unite into one output d_1 the upper (free, or idle) contact a_1 of the first selector with the lower (working) contact b_2 of the second selector, and into an input d_2 the lower contact b_1 with upper contact a_2; but to the middle (moving) contacts c_1 and c_2 we supply, respectively, impulses g_1 and g_2. Then, for the upper position of both of the middle contacts at output d_1 it is possible to take the impulse g_1, and at input d_2 it is possible to take the impulse g_2. For the lower position this distribution is changed. Therefore, with the aid of two blocks of selectors whose class-one components are commuted in a similar manner, it is possible to effect both of the possible distributions of two numbers (combinations, or sets, of impulses) with respect to the calculators s_1 and s_2. For brevity we shall discuss the operation of only the class-one components of the blocks. This, however, does not limit in any way the generality of the discussion.

It is known that each substitution S from $S^{(k)}$ is equivalent (and therefore in a great number of ways) to a product of transpositions t_i. Let $S = t_1, t_2, \ldots t_n$ be one of the possible expansions and let them, for each t_i, be set in correspondence with the two selectors, joined as in Figure 1 /omitted in the original article/. Each two outputs $d_1^{(i)}$ and $d_2^{(i)}$ of the i-th pair must now unite with the middle contacts $c_1^{(j)}$ and $c_2^{(j)}$ of the j-th pair so that for the lower positions of all middle contacts the permutation S of the impulses $g_1, g_2, \ldots g_k$ has been effected.

For a certain i let us perform a combination corresponding to the product $t_1 \ldots t_i$. Now, if $t_{i+1} = (ab)$ and a is less than b, then to the contact $c_1^{(i+1)}$ of a pair of selectors t_{i+1} is joined he input $d^{(j)}$ of the pair corresponding to the last in the series $t_1, t_2, \ldots t_i$ of a transposition t_j that permutes the symbol a, where impulse g_a has been "pro-fixed." For a greater than b the output $d^{(j)}$ unites with the middle contact $c_2^{(i+1)}$. If among $t_1, t_2, \ldots t_n$ there is not one transposition that permutes a, then g_a is immediately fed to $C_1^{(i+1)}$ for a less than b and to $c_2^{(i+1)}$ for a greater than b. Let us assume that the middle contacts of all selectors take the upper positions. In k outputs $d^{(e)}$ ($e = i_1, i_2, \ldots i_k$), remaining free after all the indicated combinations, are "pro-fixed" all impulses $g_1, g_2, \ldots g_k$, which we shall direct to the counters in such a way that the identity substitution E has been effected, i.e., for each e we shall feed to the counter s_e the impulse g_e with output $d^{(ie)}$. Now it is easy to see that if all middle contacts turn out to be transferred to the lower positions, then the distribution of impulses g_e according to counter s_e will correspond exactly to the substitution S. We note that if this transfer occurs everywhere, after exclusion of the selectors pertaining to transposition t_j, then the distribution obtained here of the numbers with respect to calculators will correspond to the substitution $t_1 \ldots t_{j-1} t_{j+1} \ldots t_n$. Moreover, thanks to the mobility of middle contacts we can affirm that the combination of selectors written above, and constant hereafter, will permit obtaining the distribution of impulses which correspond to any of 2^n substitutions: $t_1^{e1} \cdot t_2^{e2} \ldots t_n^{en}$.

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Here the symbol $e_i = 0$ or 1 and t^o signify the identity substitution E. The index $e_i = 0$ indicates the upper position of the contacts $c_1^{(i)}$ and $c_2^{(i)}$ of selectors t_i, and the value $e_i = 1$ indicates their lower position.

All this permits the problem of constructing a system of selectors that provides for all factorial-k (k!) permutations of k impulses to be specified by a certain minimum condition and permits one to invest this problem with a purely algebraic content.

In a symmetric group of the k-th degree, it is necessary to select a system of transpositions $t_1, t_2, \ldots t_n(k)$, such that the $2^{n(k)}$ substitutions

$$t_1^{e_1} \cdot t_2^{e_2} \ldots t_{n(k)}^{e_n} \quad (e_i = 0 \text{ or } 1)$$

contained the whole symmetrical group and such that the index n(k) was the least possible.

In other words, the problem reduces to the selection in $S^{(k)}$ of the least well-regulated system of generators (well regulated in the sense that for each generator all generators are indicated exactly, to which multiplication from the left and also from the right is admissible). In its characteristic of being well regulated appears the fact of constant connection between mobile and output contacts of different selectors. It is essential that some of the t_i can coincide and that the whole system be selected not uniquely.

For small k it is possible by immediate selection to find the least well-regulated systems of generators of $S^{(5)}$. Thus, for $k = 3$ the least n(3) equals 3, and it is possible to indicate, for example, the system of generators (12), (13), (23), and also the system obtained from it by variation of the order of sequence: (23), (12), (13).

For $k = 4$ the least n(4) equals 5, and, for example, the transpositions (12), (13), (24), (34), (12) form a well-regulated system of generators of $S^{(5)}$. For $k = 5$ the number is $n(5) = 8$.

It is interesting to show the law of selection of the least well-regulated system of generators in a symmetrical group of arbitrary degree k.

It should be noted that the number n(k) does not exceed C_k^2, the number of different double processes from k elements. Actually, let this fact, obvious for $k = 2$, be demonstrated for all k less than n. Each permutation of n elements $a_1, \ldots a_n$ can be expanded into a product of appropriate permutations of (n-1) elements $a_1, a_2, \ldots a_{n-1}$ and the corresponding transposition $(a_t a_n)$ $(t = 1, 2, \ldots n-1)$. Therefore, as a result of joining (n-1) transposition $(a_t a_n)$ to the C_{n-1}^2 transpositions already selected from (n-1) elements there is obtained a well-regulated system of generators for $k = n$. However, this system is a minimum only for $k = 2$ and 3 and contains, for $k = 4$ and 5, $n(4) + 1$ and $n(5) + 2$ generators, respectively.

For each substitution S the group of indices $e_1, e_2, \ldots e_{n(k)}$ in its presentation through the generators of the system determines the set, or group, of controlling notches. They must be cut on the punch cards for the numbers $g_1, g_2, \ldots g_a$, whose distribution must be obtained with respect to the counters, corresponding (distribution) to substitution S, i.e., for $e_i = 1$ in the column belonging to both selectors t_i the perforation should be punched, and for $e_i = 0$ it should not be done.

The solution of the formulation of the above problem shows that the minimum number of selectors necessary for the creation of a scheme that effects all permutations is twice the largest number n of generators in a least well-regulated system.

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